

Canadian Forces Experience with Turbofan HCF – Case Study

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SUMMARY

High Cycle Fatigue (HCF) cracking of a Canadian Forces (CF) turbofan engine fuel tube resulted in a six year, multinational effort to identify the root cause and to ultimately develop and implement a solution. The second of three fuel tube failures experienced by the CF during this timeframe resulted in an engine fire that caused significant damage to a military aircraft, underlining the seriousness of the issue at hand. With HCF identified as the mechanism of failure, efforts focused on vibration input to the fuel tube during engine operation. An experiment was developed to instrument an in-service fuel tube and perform comprehensive flight tests to quantify the strains experienced by the tube and identify vibration frequencies that required mitigation in order to eliminate HCF failures. A damper bracket was developed to shift the modal response of the fuel tube away from damaging frequencies experienced in-flight. The prototype bracket then required the addition of an adjustable feature that would allow it to accommodate slight variability in the location of mounting points from engine to engine. In addition, modification of some existing hardware was also required in order to implement the final solution. Production damper brackets were installed on all in-service engines, and to date have prevented any further fuel tube failures.

1.0 INTRODUCTION

The F404-GE-400 turbofan engine, manufactured by General Electric Aircraft Engines (GEAE), provides propulsion for the Canadian Forces CF-18 Weapons System, a dual engine supersonic tactical fighter aircraft. The F404 has been in service for the Canadian Forces (CF) since 1982 and has been continuously managed, modified and improved upon by GEAE and the global F404 community as new challenges arise during the progressing life cycle of the engine. The CF encountered an issue in 1998 involving High Cycle Fatigue (HCF) that became the basis for a six year, multinational effort to obtain a concise understanding of the problem. During this period, efforts were aimed at developing and implementing a solution while simultaneously mitigating the risk that this issue posed to the global F404 fleet. This paper documents the experience of the CF during this timeframe, from discovery of the issue, through the investigation, development, testing and implementation of the final solution.

2.0 THE FIRST INCIDENT

During routine engine operation on the ground at Canadian Forces Base (CFB) Cold Lake in August 1998, a fuel leak was observed originating from the left hand engine of a CF-18 aircraft. The engine was shut down without incident, and was removed from the aircraft for further investigation. Upon disassembly of the engine, the main Lower Fuel Manifold (LFM) was discovered to be cracked.

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The LFM, shown below in Figure 1, is a semi-circular tube encompassing the lower half of the Combustor Case. The LFM carries pressurized fuel to the fuel nozzles of the engine where it is then mixed with compressed air and ignited within the Combustor Case. Incoming fuel is fed to the LFM via an inlet tube located at the 6 o'clock location of the assembly. Fuel is then split between the left and right sides of the Combustor Case at a welded T-junction in the LFM. The incident assembly described above was found to be cracked in the heat affected zone of one of the three welds at this T-junction.

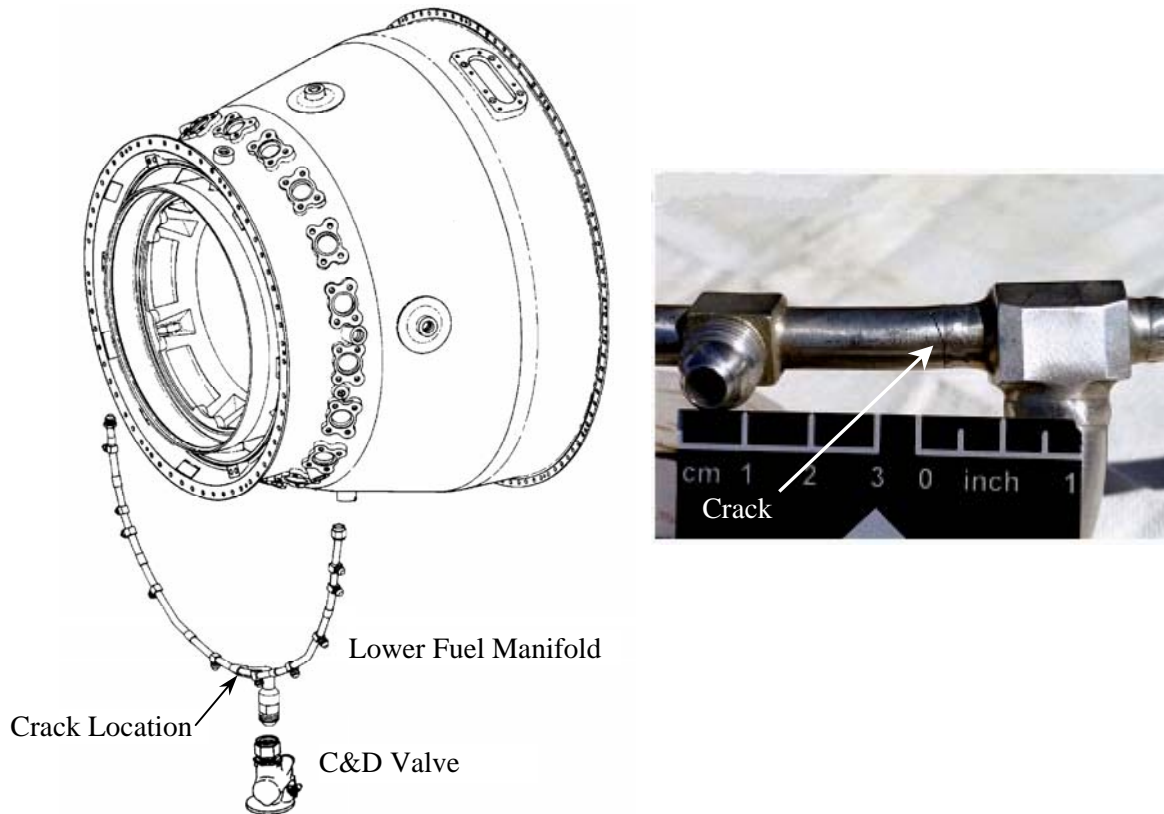


Figure 1: Lower Fuel Manifold

The cracked LFM was removed from the incident engine and forwarded to GEAE for investigation. Although no manufacturing or design defects were found to explain the cracking, fracture surface analysis indicated that the LFM cracked due to High Cycle Fatigue (HCF). GEAE's conclusions suggested that assembly stresses may have led to the fatigue cracking (since this LFM was not the original component).

The LFM is affixed to the Combustor Case using simple bracket assemblies at seven separate locations. During engine assembly, a Check & Drain (C&D) Valve is threaded onto the lower inlet tube of the LFM and a torque of approximately 1000 lb-in is applied. Although a wrench flat on the LFM fitting allows the inlet tube to be restrained during torquing of the C&D Valve, technicians found it difficult to prevent the LFM from twisting, even when two technicians were performing the operation. Therefore, the potential transmission of significant stresses to the LFM inlet tube (and consequently to the LFM T-junction) during engine assembly became the focal point of the investigation.

As a result, a specialized tool was developed to aid in reducing the stresses experienced by the LFM during torquing of the C&D Valve. The tool was designed to be firmly attached to the engine using existing bolt holes while simultaneously restraining the LFM inlet tube from being twisted. Figure 2 illustrates the tool that was developed.



Figure 2: Lower Fuel Manifold Restraining Tool

In addition to the development of the LFM Restraining Tool, a formal review of engine assembly procedures was carried out to ensure that technical manuals were as clear and concise as possible. Several modifications were made to the technical manuals, including the addition of numerous “Cautions” to ensure technicians were aware of the importance of adequately restraining the LFM during torquing of the C&D Valve and the potential consequences of improper assembly. The CF would not experience another LFM related incident for three years.

3.0 THE SECOND INCIDENT

Shortly after takeoff from CFB Cold Lake in August 2001, and after reselecting a throttle setting of maximum afterburner, a CF-18 pilot received audible cautions for a left engine fire. The pilot activated the left engine bay fire suppression system and shut down the incident engine before carrying out a single engine landing without further incident. A preliminary survey revealed multiple ruptures in the afterburner case of the incident engine, through which hot gases escaped, causing significant damage to the airframe. Internal inspection of the incident engine using remote visual inspection equipment revealed a crack in the T-junction of the main LFM. It was concluded that fuel leaking from the cracked LFM was ignited when the pilot advanced the throttles into afterburner operation. Figure 3 depicts damage to the incident engine as well as the cracked LFM.

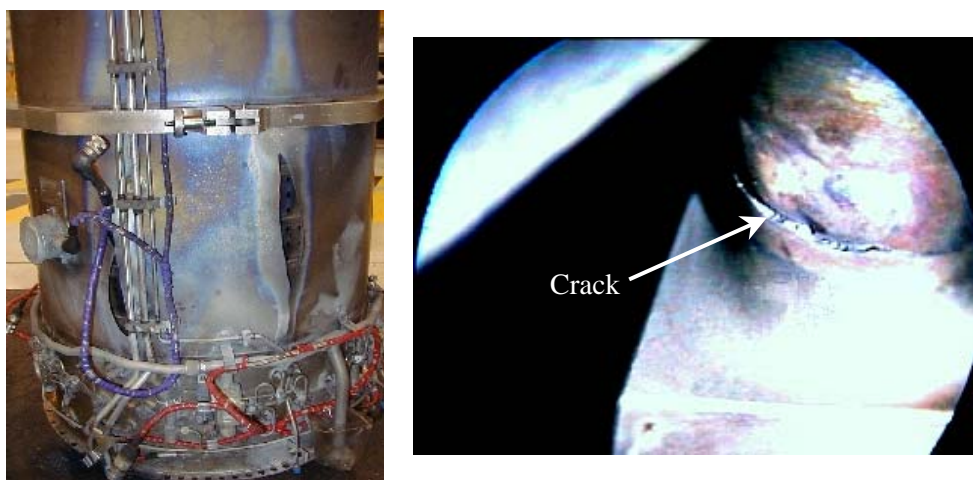


Figure 3: Damaged Engine and Cracked Lower Fuel Manifold

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The engine was removed from its airframe and forwarded to Magellan Aerospace where a controlled disassembly was carried out, documenting the condition of all pertinent hardware and ultimately confirming the cracked LFM. An extensive review of all recorded engine parameters during the incident flight was also carried out in order to gain a better understanding of how the engine performed while being starved of fuel as a result of the cracked LFM. Shortly thereafter, GEAE confirmed HCF to be the mechanism that caused this second LFM cracking event and subsequently recommended that all F404 users take the necessary steps to increase the inspection frequency of all installed LFMs.

In light of the severe circumstances of this second LFM cracking event, a team was convened in October 2001 with a mandate to determine the cause of the LFM cracking and to develop a suitable solution. The team consisted of members from GEAE, the CF and Magellan Aerospace, as well as members of another foreign military organization using the F404. The investigation began with the gathering of information, primarily concerning the engine/aircraft configurations that experienced the two LFM cracking events to date. The team quickly agreed that, because HCF was the mechanism causing the fuel tube cracking, an LFM would be instrumented and installed in a test engine which would undergo flight testing to determine the frequency and magnitude of vibrations that the LFM experienced under as many operating conditions as possible.

4.0 TESTING

4.1 Flight Test

The Aerospace Engineering Test Establishment (AETE), located at CFB Cold Lake, carries out engineering evaluations of the airworthiness and operational effectiveness of CF aerospace systems. The CF enlisted AETE to provide a test aircraft and support team to aid in the development and execution of a test plan to evaluate the effects of operational strain on the F404 LFM. Testing of an instrumented LFM first required the assembly of a test engine. With a goal of recreating the conditions of the second LFM failure as closely as possible, the 2001 incident engine was deemed the best candidate for testing. With the exception of fire damage to the afterburner, the engine remained intact and was rebuilt in January 2002 using as much of the incident hardware as was possible.

An instrumented LFM was provided by GEAE for the engine test. The tube assembly was equipped with eight strain gauges, four on either side of the T-junction, at evenly spaced intervals around the tube circumference as shown in Figure 4.

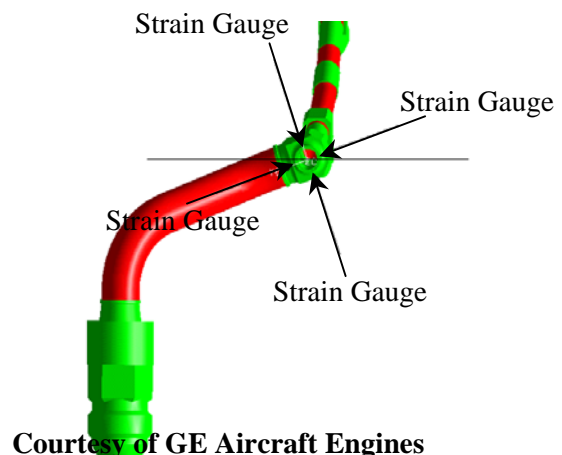


Figure 4: Instrumented Lower Fuel Manifold

During installation of the instrumented LFM, static strain gauge readings were taken before and after each step of the build-up, not only to quantify installation stresses, but also to ensure that all gauges continued to function normally. Unfortunately, during the installation, one of the strain gauges stopped functioning and several other gauges reported strains suggesting that the LFM material had been stressed beyond the yield strength, which was highly suspect. Because it was unclear whether these readings were accurate, concerns were raised regarding the integrity of the LFM and the possibility of an in-flight fuel leak during flight tests. In addition, beginning the operational testing of the engine with strain gauges that were already reporting unexpected readings would devalue the entire flight test program. As a result, the instrumented manifold was removed from the engine, and a second instrumented manifold was installed. No unusual strain measurements were reported during the second LFM installation, and all gauges continued to function normally. Unfortunately, this unexpected hardware replacement required a considerable amount of time to correct and highlights the sensitivity of carrying out such an experiment in the field.

While the test engine was being assembled, the investigating team began creating flight test plans to evaluate the instrumented LFM. With input from multi-national flight test specialists, a test matrix was developed that included aggressive manoeuvring at various altitudes, airspeeds and angles of attack, all with varying throttle positions in order to evaluate LFM strain throughout the entire operational envelope of the F404 engine. Several engine starts and maximum afterburner takeoffs were also included in the test matrix. Due to cost limitations and test aircraft availability, the flight test matrix was carefully developed to maximize the number of test points that could be performed in a minimum number of missions. At the time, most F404 users had converted from JP4 fuel to various alternatives, however the CF had not yet made the transition and were still using JP4 fuel. It was felt that this unique operating parameter may have been a factor in explaining why the CF were the only F404 users experiencing LFM failures. As such, the flight test matrix was to be flown twice: first using JP4 fuel, and again using JP8 fuel to determine if the LFM experienced any appreciable difference in strain levels between the two fuel types. However, before this investigation was completed, other F404 users operating on other fuels would experience a number of LFM failures, negating this aspect of the investigation.

Flight tests began at AETE in June 2002, which required approximately two weeks in order to carry out all of the required test points over four missions using both JP4 and JP8 fuel. Several accelerometers and a thermocouple were added to the LFM and surrounding engine/airframe hardware to evaluate dynamic tri-axial acceleration and local temperature during the flight tests. These readings, along with the LFM strain signals and all engine and aircraft operating parameters were transmitted from the aircraft to the Flight Test Control Centre via telemetry. In addition to the flight tests, several “ground runs” were carried out to evaluate LFM strains during throttle movements with the aircraft on the ground. Upon completion of all tests, the recorded data was provided to GEAE for analysis.

Analysis of the AETE flight test data revealed several resonant frequencies during various engine operating regimes and aircraft manoeuvres. The maximum LFM strain measured over all test points occurred during the JP8 fuel portion of the tests under a high-g, high angle of attack, subsonic turn. During this manoeuvre, a low frequency input pushed the LFM strain to 100% of the design maximum allowable. Conversely, the strains measured during “straight and level” flight were significantly lower, and nearly negligible during ground testing. These flight test results suggested a clear correlation between aggressive aircraft manoeuvring and high LFM strains. This would help to explain why many LFMs in service were able to accumulate far greater flying hours than those that failed due to HCF without incident. It would also explain why F404 applications other than the F/A-18 had experienced no LFM failures.

4.2 Bench Test

While flight tests were being carried out at AETE, GEAE was developing a shake table test with the intent of duplicating the strains experienced by the instrumented LFM during flight testing under laboratory

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conditions to facilitate evaluation of mitigation options. An instrumented LFM was installed on a Combustor Case with all pertinent hardware as well as simulated interaction between the C&D Valve and the airframe. This apparatus was oscillated in three planes through a 0 – 2000 Hz frequency sweep while measuring the strain induced in the LFM. Figure 5 depicts the shake table testing set-up.



Figure 5: Shake Table Testing Set-up

The frequency sweep identified the first seven resonant modes of the installed LFM, with the first and lowest frequency mode nearly identical to the frequency at which the highest LFM strain level was measured during flight tests. This comparison allowed GEAE to use the shake table to accurately reproduce the strain conditions experienced by an LFM during engine operation with excellent correlation. An LFM endurance test was carried out with oscillations at moderate amplitude (approximately 65% of the design maximum allowable strain at the LFM T-junction) within the low frequency range of interest identified during both the flight tests and the frequency sweep tests. The endurance manifold eventually failed in nearly identical fashion to those that were discovered cracked in service, which not only validated the laboratory set-up, but also provided a baseline against which any mitigation options could be tested.

A root cause, in the purest sense of the term, was not identified for the HCF failures of LFMs experienced by the CF and other F404 users. Ultimately, the source of low frequency vibration that induced damaging strain levels to the F404 LFM was thought to be oscillations of the airframe vertical stabilizers during high angle of attack and high-g manoeuvres, although this theory was never proven. However the investigating team was now equipped with a clear picture of the types of strains experienced by an installed LFM during nearly all operational regimes. This allowed investigators to effectively evaluate any and all potential solutions and ensure that damaging strains were adequately mitigated, reducing the associated risk of failure to an acceptable level.

5.0 THE SOLUTION

A number of options were explored for possible solutions to the LFM issue, including consideration of a complete redesign of the LFM. However, due to the complexity of the part and its role as a pressurized fuel tube, such a redesign effort would have required a substantial amount of time and monetary investment to complete. With the potentially severe consequences of further LFM failures well understood, the CF and other F404 users were seeking a solution that could be developed more quickly, and would require minimal effort to implement. Focus was then applied to reducing the input of damaging vibration to the LFM T-junction.

GEAE has long incorporated damper brackets in commercial aircraft engines to reduce strain on fuel manifolds due to engine vibrations. Consequently, a damper bracket was the most logical solution to solve

the F404 LFM issue since GEAE design experience would minimize development time and cost. The addition of the damper bracket to the LFM assembly would shift the first modal response of the system away from the low frequency input identified during flight tests. Therefore, existing low frequency vibration resulting from engine operation would no longer create a resonant response in the LFM assembly, thereby significantly reducing operational strain at the LFM T-junction. By September 2002, GEAE had developed a prototype damper bracket for the F404 that was installed on the laboratory calibrated shake table test bed to make an initial assessment of its ability to mitigate LFM strain. The prototype damper bracket consisted of three basic components. Two halves of the bracket spanned the distance between the C&D Valve (attached to the LFM inlet tube) and the Outer Bypass Duct (OBD). A spring and stud that provided the dampening feature of the bracket system joined the two bracket halves together. The bracket was designed to be bolted directly to the OBD using existing boltholes, and would interface with the C&D Valve Fuel Hose, which bolts directly to the C&D Valve and provides main fuel flow to the LFM. During engine operation, the bracket would restrict vibration of the LFM at the C&D Valve interface regardless of the source of vibration. Figure 6 depicts a rendering of the damper bracket installed on the F404 engine, showing how it is incorporated with existing hardware. Note that the damper bracket was designed to be installed on the outer shell of the F404 engine, and could therefore be installed without engine disassembly, and could even be installed on engines mounted in airframes. This greatly simplified the logistical planning for incorporation of damper brackets across the entire CF F404 fleet.

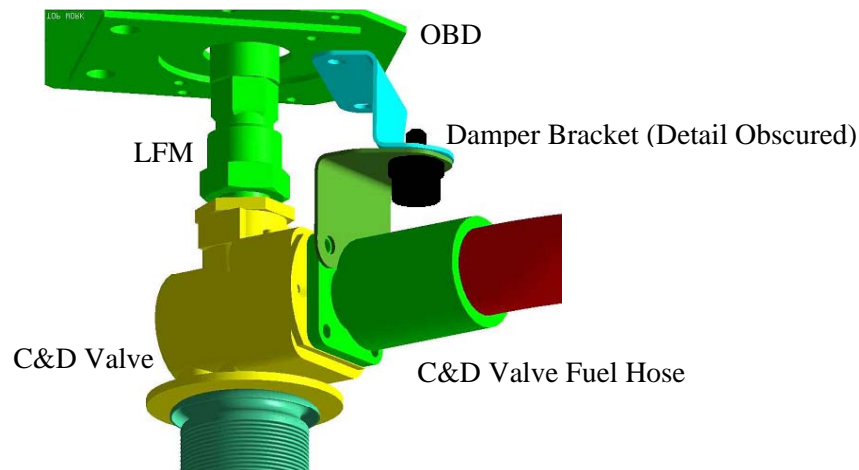


Figure 6: Prototype Damper Bracket Design

In November 2002, the prototype damper bracket was installed on the shake table test bed at GEAE with a new LFM to evaluate the ability of the bracket to reduce strains at the LFM T-junction induced by vibration inputs at the low frequency range of interest. With the shake table operating at the same frequency and amplitude as for the baseline test, the number of cycles accumulated was five times greater than that required to fail the LFM in the first test with no damper bracket installed, and the new LFM remained intact at the conclusion of this second test. The measured strain at the LFM T-junction was reduced by as much as 94% at the low frequency range of concern with the damper bracket installed versus the strains measured during the baseline shake table tests without the damper bracket. Although the bracket was not as effective at reducing higher frequency modes of vibration induced strains, some mitigation was afforded at these higher frequencies through both direct dampening, as well as by shifting several modal responses of the LFM/damper bracket system away from the damaging resonant frequencies of the installed, unmitigated LFM. Unfortunately, while these tests were being carried out, the CF operational fleet had its third LFM cracking event at CFB Cold Lake, which resulted in a fuel leak.

By April 2003, a production version of the LFM damper bracket was produced by GEAE and was used for trial installation on an F404 engine at Magellan Aerospace. During the trial, it was discovered that

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variability in the position of the C&D Valve with respect to the OBD meant that the mounting points for the two damper bracket halves could be of varying distances apart. This created a condition where the two bracket halves would become slightly separated, leaving a small gap between the two halves, and creating an undesirable possibility for abnormal wear of the damper bracket as well as the possibility of compromised dampening effect. This necessitated a redesign of the damper bracket in order to incorporate some adjustability that would allow the bracket to be adaptable to the varying installation conditions on all F404 engines. By May of 2003, a newly designed bracket had been produced by GEAE, which incorporated a feature that would allow the length of one half of the damper bracket to be adjusted in order to span the varying distance between the mounting points on the C&D Valve and the OBD. Figure 7 is a photo of an installed damper bracket, conveying the challenge of incorporating a new component within the complex network of existing engine hardware.

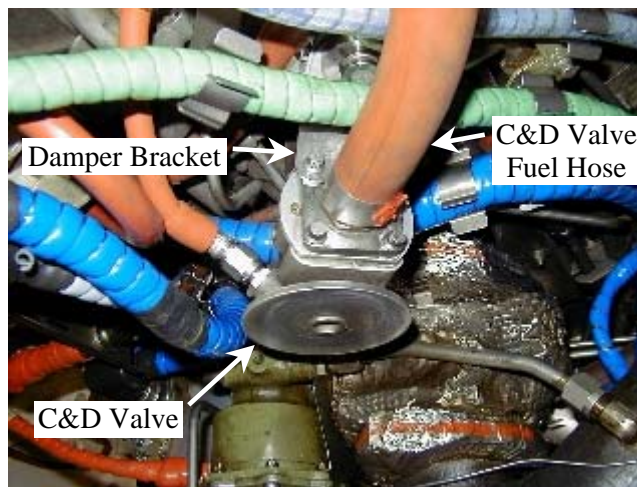


Figure 7: Second Damper Bracket Design

Trial installations were carried out on an F404 engine using the newly designed damper bracket with no further complications. The adjustable feature of the new bracket allowed the system to compensate for the variability of mounting point positions between engines and allowed proper installation of the bracket with little increase in complexity or effort. The new bracket was forwarded to CFB Cold Lake in July 2003 in preparation for flight tests at AETE during the following month. Before testing the new damper bracket, baseline flight tests were performed without the bracket installed in order to re-establish the measured strain levels experienced by the LFM in flight and to ensure that the results had not changed significantly from those recorded during the June 2002 flights. The same test matrix was flown as during the previous flight test phase, however this time only JP8 fuel was used. Upon completion of the baseline flight tests, the recorded data was analyzed and found to be very similar to that recorded during the June 2002 flight tests. The damper bracket was then installed and the flight test matrix was repeated.

Analysis of the damper bracket flight test data was completed in September 2003 with the results indicating that with the damper bracket installed, overall strain levels at the LFM T-junction were reduced by approximately 48%, well below design maximum allowable levels. The damper bracket was found to be extremely effective in mitigating vibration input to the LFM in the low frequency range of concern that was identified during the 2002 flight tests. Based on these results, all parties involved in the development of the damper bracket agreed that the flight tested design was sufficient in its ability to mitigate undesired strain levels in the LFM T-junction and reduce the risk level associated with this issue to an acceptable level.

6.0 IMPLEMENTATION

Delivery of production damper brackets to the CF began in November of 2003, at which time preparations were being made to begin an installation campaign to incorporate the bracket across the entire CF F404 fleet. During these preparations, it was acknowledged that some engines could potentially require additional consideration in order for them to accept the damper bracket in the form of modification of an existing component. As mentioned above, the damper bracket was designed to be bolted to the OBD and C&D Valve at existing bolthole locations. The two boltholes at the C&D Valve are also used to bolt the C&D Valve Fuel Hose to the valve. The metal flange of this fuel hose, which the damper bracket was designed to interface with, had to be flat in order for the bracket to be properly secured. However, many of the C&D Valve Fuel Hoses were found to be of a configuration that had forged flanges that were not flat at the C&D Valve. Instead, they had a raised portion between the boltholes as depicted below in Figure 8.



Figure 8: C&D Valve Fuel Hose Flange

A procedure was developed to machine the raised portion of the C&D Valve Fuel Hose flange flat for proper interfacing with the new damper bracket. A field modification instruction was created in order to document the machining procedure, which could be carried out in the field during incorporation of the new damper bracket. Modification of this fuel hose meant that a small percentage of parts would be lost due to errors during machining and because some parts would not meet minimum requirements to be eligible for modification. As such, additional C&D Valve Fuel Hoses had to be purchased by the CF in order to offset these losses.

Once the field instructions for installation of the damper bracket and modification of the C&D Valve Fuel Hose were released, all in-service CF engines were required to have the damper bracket incorporated within a limited number of flying hours to ensure that brackets were installed across the entire fleet as quickly as possible. Due to the limited space in the area of the new damper bracket, a follow-up inspection requirement was issued approximately eight months after the CF began installing damper brackets. This instruction required inspection of each C&D Valve Fuel Hose as well as other surrounding tubes and hoses for any signs of damage due to contact with either other hoses/tubes or the damper bracket. Any unserviceable hardware was replaced or adjusted as necessary.

By January 2005, the CF had installed damper brackets on all in-service engines across the entire CF-18 fleet. The CF have not had an LFM cracking incident since March 2003, and continue to closely monitor installed damper brackets and LFMs for any signs of unserviceability or unforeseen conditions. Despite the risk reduction afforded by the incorporation of damper brackets across the F404 fleet, all LFMs that were in service prior to incorporation of the damper bracket may have been exposed to damaging strains induced by unmitigated vibration. Therefore, the CF plan to replace all LFMs that have been in service without the benefit of a damper bracket on an opportunistic basis to ensure that the risk associated with HCF failure of LFMs is minimized. Efforts are currently underway to acquire the necessary hardware to support this replacement campaign.

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7.0 CLOSING REMARKS

From recognition of the problem to a fully implemented solution, the HCF issue that affected F404 LFMs took approximately six years to address in its entirety and required the participation of a large multinational contingent of expertise. This case study effectively demonstrates the complexity of addressing a major issue posing a significant risk to a military aircraft system. Beyond identifying HCF as the failure mechanism of F404 LFMs, the vast amount of logistical effort required to support the entire effort must be recognized. From the initial risk abatement to the multinational co-ordination of experimental flight tests, development of a prototype solution and implementation of airworthy production parts, a staggering amount of time and effort was expended in order to ensure that the CF-18 Weapons System was able to function effectively and with an acceptable level of risk throughout the entire ordeal. All of this effort was conducted beyond the realm of academic theory, in the vast organization of a real-world operational military air vehicle fleet.

SYMPOSIA DISCUSSION – PAPER NO: 18

Author's name: C. Kinart

Discussor's name: G. Harrison

Question: During the 6 years taken to implement a satisfactory solution, did any nations indicate they also experienced problems?

Answer: Yes, other nations had experienced issues related to the lower fuel manifold, although few to the degree experienced by the Canadian Forces (i.e. In-flight fire). The damper bracket was introduced to all F404 users via GE's engineering change proposal (ECP), which gave all users the opportunity to incorporate the damper bracket if they so chose.

Discussor's name: Dr J. Hou

Question: Was this case study carried out under F404 of CIP?

Answer: Yes, GE's component improvement program was involved in the development of the damper bracket following the August 2001 incident.

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